SPE 140630

Sustenance and Management of a Matured Waterflood - A Niger Delta Case Study

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This paper was prepared for presentation at the 34th Annual SPE International Conference and Exhibition held in Tinapa – Calabar, Nigeria, 31 July–7 August 2010.

Abstract

The field started production in 1965, it is structurally complex, comprising of several structural closures contained within three major fault blocks. The flooded reservoir block discussed in this paper came into production in 1965. Rapid pressure decline (55 psi per 1 % of STOIIP produced) was observed in the early production life of the reservoir.

The rapid reservoir pressure decline caused shrinkage losses and expansion of the gas cap; this in turn resulted in production problems. A case for water injection was made & full-scale water injection commenced in 1978 with 3 injection wells taking water from a shallow aquifer through 2 source water wells. In addition to arresting further reservoir pressure decline, the project protects a reservoir production rate of 3.5kbopd and safeguards up to 10 MMstb remaining reserves.

The water injection project like many matured waterflood systems operated under matrix conditions was plagued by frequent loss of injectivity & surface facility integrity issues coupled with the peculiar security situation of the Niger Delta.

This paper describes;

- *How well & surface challenges with the water injection project have been resolved*
- *Continuing operational and performance monitoring methods to sustain and optimally manage the peripheral water injection*

Introduction

Water flood or water injection is commonly used in oilfield developments for optimization of reservoir sweep and for pressure support or maintenance.

A water injection project will generally consist of:

- A surface facility designed to process water & inject water into the target reservoir
- Injection well(s) completed in the target reservoir requiring pressure maintenance
- Sustainable water source, which could be source well(s), completed in aquifer sands, produced water from oil producing wells (PWRI-Produced Water Re-Injection) or seawater if offshore.

Based on source water quality & desired injection rates, the water injection strategy could be:

- Matrix
  - injection pressure is below formation fracture pressure
- Fracture
  - injection pressure is above formation fracture pressure
- Matrix- Fracture
  - a combination of both

The case study is an onshore water injection project into a shore face reservoir with a thickening upward profile. It is a normally pressured system with initial datum pressure of 3150psi. Fluid properties are moderately light– (Rsi = 387scf/bbl ; Boi = 1.14rb/d, 3.53cp; Oil gravity of 23 API).

Production from the reservoir block (which we will call WIP_1) started in 1965 and peaked at an average withdrawal rate of circa 10,200 bopd, 8 Mmscfd at 0% water cut with 4 oil producers. Early reservoir performance revealed relatively rapid pressure decline indicative of little or no voidage replacement. Currently 2010), the reservoir block is produced by 8 conduits at 3,600 bopd, 3.5 Mmscfd and 40% avg BSW.

CASE FOR WATER INJECTION

The need for an effective pressure maintenance scheme was recognised early in WIP_1's production life, as key to maximizing its recoverable hydrocarbon in view of the strength of the natural water drive mechanism. Of the various methods considered, peripheral matrix water injection was chosen largely due to source water availability, reservoir dynamics and relative modest operating cost. Figure 2 shows WIP_1 water injection project was started fully in 1978 with injection in 3 wells (Wells 1, 2 & 3) using water from source wells 4 & 5 (shallow aquifer –WS_1) following a successful pilot in 1974. The pilot scheme comprised two wells –One each of water producer (well 4) and water injector (well 1). Results show that the reservoir pressure fairly stabilized through the period when water injection continued indicating good pressure support from the water flood.

WIP_1 is a 150 MMstbo and 97 Bscf hydrocarbon system. The rapid reservoir pressure decline caused shrinkage losses and expansion of the gas cap; this in turn resulted in production problems. By early 70s, at an average withdrawal rate of 4.7kboepd, the reservoir pressure depleted at the rate of 48.5psi/Mmstboe.

HISTORICAL WATER FLOOD CHALLENGES

Wells:

Injector wells are vertical with single zone completions in the water leg of the WIP_1 reservoir ca 7500ftah. Being a poorly consolidated reservoir all injection & production intervals have some form of sand control, mostly internal/open hole gravel pack (IGP).

Injectors are equipped with 3-1/2" or 2-7/8" tubings with gas lift mandrels (GLMS) & 9-5/8" casings.

Producers are all equipped with GLMS.

Source water wells are completed as vertical annular producers with gas lift injection through the 2-3/8" tubings and water production via the 7" casing. IGP completions in a shallow compatible large aquifer ca 2600ftah.

Summary of Well Challenges:

- Continuous decline of well injectivity necessitated a number of re-entries and stimulation treatments to improve the injectivity of the wells.

-Sand control failure evidenced by gravel pack sand recovery.
-Corroded tubing.

Soln: Wells were repaired during rig workover activities.

-Decline in injectivity;

-due to bacterial action evidenced by bailed deposits of black sandy looking corrosion products of sulphate reducing bacteria (SRB) action. When SRB colonies are not monitored & appropriate controls through biocide treatment regimes are not implemented.

Soln: Backflushing operations using gaslift through GLMS & bacteria treatment- 1st option.
Coiled tubing clean out if 1st option fails to restore injectivity, then bacteria treatment.

-plugged perforations/gravel pack screen due to accumulation of solids (iron scales from tubulars, sand etc) due to ineffective filtration or corrosion of tubular downstream of the filters.
-formation fines migration into the wellbore during shutdown

Soln: Backflushing operations using gaslift through GLMS- 1st option.
Coiled tubing clean out followed by acid treatment (3% NH4Cl brine, 7-15% HCl preflush, HCl:HF mud acid, 3% NH4Cl afterflush) with immediate resumption of injection.

-(rarely) oily deposits recovery indicative of liquid carryover in the gaslift system used for lifting the source water.

Soln: Backflushing operations using gaslift through GLMS- 1st option.
Coiled tubing clean out followed by emulsified 7-15% HCl (20-30% Xylene) acid treatment.

Notes: When solid recovery is available from wells, laboratory analysis is done to select best stimulation treatment recipe. These above are generally what was required for this system and would be similar in most sandstone reservoir water flood systems. Knowledge of the mineralogy & water chemistry will help to fine tune the recipe for higher chances of success, reducing the risk of formation damage from stimulation activities.

Backflushing or flowing back the water injectors have improved injectivity with a success ratio >50% at almost zero cost.

Surface Facility:

Surface facility for water processing and injection consists of 4-6" flow lines, 2" gas lines, a low pressure horizontal separator, a vertical surge vessel, 2 high volume pumps, chemical injection pumps, metering equipment & guard cartridge (Cuno) filters at well locations.

Summary of Surface Facility Challenges:

The wellhead filters are often plugged due to the quality of water reaching them after passing through a few kilometres of old/rusty flowlines.

Soln: Change out the filter elements on regular basis or when perceived plugged/damaged as indicated by downstream water sample or pressure differential. Post shut down, bypass filters while flushing lines till water quality is acceptable before routing through filters & into wells.

-Corrosion leaks.

Soln: sections of lines are replaced when leaks occur or based on results of ultrasonic wall thickness checks. Ensure the biocide & corrosion prevention chemical injection regimes are followed or revised as required.

-Vandalisation.

Soln: replacement of vandalised or stolen lines & wellhead accessories. Replacement of carbon steel flow lines with coated GRE (glass reinforced epoxy) that are buried with minimal exposure except at the wellhead & use of anti-theft nuts. Surveillance contracts & security plans are reviewed regularly.

-Metering error. Barton meter/Daniel Orifice Fitting (DOF) assemblies are used in this water flood scheme. This gives high error margins due to subjective chart readings by operators & it is not quite accurate for 2-phase flow.

Soln: Operator training in meter usage. Correct factor selection with appropriate orifice plate size use. Change to better more appropriate liquid meters (positive displacement -PD, coriolis etc).

Notes: Injection system monitoring for corrosion, water quality & steadfast treatment regime (biocide, corrosion etc as required) is essential for sustenance & keeping the water flood scheme cost effective. Filtration should be good enough (particle size & concentration) to prevent plugging of the downhole sand control (if any) and the perforations. Formation water, injection water & treatment chemicals compatibility and appropriateness should be confirmed in the laboratory.

Waterflood Interruption:
Water injection stopped in 2004 because of mechanical problems at the plant and also due to high backpressure caused by impaired injection wells. During this period, most of the surface facilities including flow lines, gas lines and wellhead accessories were either vandalized and/or in dilapidated form. The effect of the loss of injection support was obvious early with the declining trend in the reservoir pressure. See Figure 1.

It took little effort to justify the resuscitation proposal as the prize was significant – These include

- Protecting current 3500 bopd average production rate from the WIP_1 reservoir
- Arresting further decline in the WIP_1 reservoir pressure.
- Safeguarding recovery of the remaining ~ 7 MMstb. Supplementary recovery by water injection expected to increase UR by 10MMstb.
- Compliance with statutory and regulatory requirement for project reservoir depletion.

The resuscitation comprised of these key activities

- Maintenance work – Overhaul of plant's critical equipment – pumps, metering devices, filters & surveillance equipment.

- Engineering – Flow lines and pipeworks to all injectors and waste pits were repaired and/or replaced.

- Well Services – All injectors were backflushed and stimulated and wellhead repairs carried out.

- Operations/Production Chemistry – Injection flow lines were pickled and flushed to acceptable specifications. All injectors' Cuno (cartridge) filters were serviced, ensured continuous corrosion inhibitor/biocide treatment administration and general project monitoring.

- Development – Anchored proposal justification and execution process. Provided analyses to support project scope and performed well/reservoir evaluation to set injection targets.

Notes: Integrated team of surface & subsurface disciplines' common understanding & purpose is essential for a successful water flood scheme especially a matured one.

The filtered (10 microns) water is injected under matrix conditions with a maximum allowable surface pressure calculated and set at 800psi. All injectors have been injecting with less than 100psi injection pressure since re-start.

WATERFLOOD MAINTENANCE AND SUSTENANCE STRATEGY

Efforts have intensified in recent times to sustain (and improve) aspects of its operation and monitoring. These can be viewed from both surface and sub-surface perspectives.

At the **surface** operations front, a number of water injection operations guidelines are being promoted and established to be part of routine operation. These include standardizing shutdown and start-up sequence, regular wellhead visits and data measurements, continuous availability and injection of corrosion inhibitors and regular biocide treatment in the right quantity based on daily water injection volumes.

Regular water quality (residual chemicals, dissolved gases - oxygen, carbon dioxide, hydrogen sulphide, solids content – total suspended solids, Iron content etc) monitoring to ensure suitability for injection.
In general, the aim is to keep the operation philosophy of water injection Plant/system active and alive.

Technical limit diagram for the plant is also updated to ensure system constraints/bottlenecks are promptly identified and corrective measures are effected as required.

Effective prediction of future oil recovery and reservoir performance for a water injection project provide basis for economic evaluation of the relevance and profitability of the project. This performance requires regular monitoring to track trend and promptly identify deviations from plan.

Subsurface Injection performance is being monitored by regular bottom hole pressure surveys (conduits do not have permanent downhole gauges), injectivity/Falloff tests, material balance analyses, history-matched simulation model and well nodal analyses. Hall Plots (product of wellhead pressure & time versus cumulative water injection) are used for injectors' performance evaluation (Figure3a).

Bottom hole pressure surveys are typically carried out for earmarked producers at an average frequency of one conduit in the reservoir per quarter. In addition to providing data for model performance calibration, these data are used to monitor changes to skin and reservoir pressure (Figure 3b & 3c).

Reservoir voidage Plots (Figure 4) have also been used to monitor voidage rate and impact on reservoir performance. This plot which excludes water influx consideration indicates cumulative voidage to date in reservoir barrels. About 32% of these have been replaced via water injection in the WIP_1. This is in line with the reservoir depletion strategy of maintaining reservoir pressure at or close to 2000psi – the pressure when full water injection commenced. The option of WIP_1 re-pressurization has been considered but dropped due to limited incremental value/recovery.

Mass balance analyses show that water injection is circa 40% of WIP_1's reservoir energy. Figure 5 is outline of the WIP_1's energy balance which interalia, indicates that the water influx impact is not insignificant but clearly insufficient to sustain/attain reservoir potential. The chart also shows expected decrease in water injection energy ratio during WIP shutdown period.

WIP_1 Producers' performances are also good indication of injection performance. Increasing trend in producing GOR always follow prolonged water injection downtime. Although injection and withdrawals are monitored to maintain reasonable voidage balance,
In general the individual well performance indicate that the injection of water has been successful in establishing reservoir pressure and allowing wells production at acceptable GOR's. Annual asset surveillance activity planning includes injectivity and Falloff tests for all existing WIP_1 injectors. Figure 6 shows result of a recent test on well 1 from which relevant well and reservoir data was obtained.

A key aspect of water injected/flooded systems is the sweep efficiency being achieved. Monitoring sweep performance is essential yet difficult to track satisfactorily. A major issue was that the injected water is fresh and therefore not easily detectable by the common method of logging with a pulsed neutron-logging tool. It therefore became necessary to select other reservoir sweep observation methods.

WIP_1 reservoir simulation modeling was used, built and history matched to assess mainly macroscopic sweep efficiencies. Figure 7 shows simulation saturation plot with area and vertical sweep patterns. No evidence of viscous fingering is observed.

Reservoir displacement efficiencies can be evaluated with fractional flow (ratio of flow of water at any point in the reservoir) curves. WIP_1's Fractional Flow (Figure 8a) indicates favourable displacement potential and historical reservoir water cut performance (Figure 8b) shows a comparable trend.

Displacement efficiency curves from (Special Core Analyses (SCAL) data indicate an ultimate oil recovery potential of 50 - 55%

Another monitoring tool adopted for this water flood is reservoir surveillance map (RSM). Reservoir surveillance mapping involves an integrated reservoir-wide management process that facilitates not only understanding syn-production subsurface dynamics but also delivering a forward cycle work program for subject reservoir/field. WIP_1 RSM (Figure 9) displays latest saturation distribution based on actual performance.

Surveillance maps for a water flood system like this are particularly unique as both dynamic and static fluid contacts can be delineated for reference.

Historically, WIP_1 production performance has indicated a direct relationship with water injection levels. Periods of reduced or no water injection as was the case between 2004 and mid-2007 typically correspond to periods of steeper production decline. The resuscitation and sustenance efforts since re-start have noticeably arrested the decline trend as shown in Figure 10.

WIP Health Check And SWOT Analysis

As part of the improvement planning and realization plan, a water flood specific health check was carried out to establish status and develop forward plan. This is consistent with the Well & Reservoir Management minimum standard provision and aligns to Strength-Weakness- Opportunity-Threat (SWOT) analyses. Figure 11 is the summary of the SWOT analyses that informs key focus areas required to sustain and improve overall water-flood performance.

The analysis highlighted several existing and potential weaknesses in the system. An improvement implementation plan was developed for inclusion in the business and surveillance activity plan.

CONCLUSION

Reservoir & Well performance indicates that the injection of water has been successful in stabilizing reservoir pressure and production of wells at acceptable GOR's.

Resuscitation of the Plant was important to consolidate on the significant gains of historical water injection, safeguard production/ reserves and ensure compliance with statutory requirements.

Recent Health-check and SWOT analysis has helped identify existing + potential strengths and weaknesses of the water-flooding scheme. Active performance monitoring tools remain key to sustaining and improving water injection performance.
Integrated team of surface & subsurface disciplines' common understanding & purpose is essential for a successful water flood scheme especially a matured one.

Active water quality monitoring to ensure it meets set specifications will both ensure asset integrity & sustenance of injectivity in a matured waterflood operated under matrix conditions.

Acknowledgement

The authors wish to thank the management of SPDC Asset Development and Petroleum Engineering Discipline Teams for granting the permission to publish this paper.

The 2007 waterflood resuscitation team of SPDC for their dedication to quality and timely delivery of the project;
Falowo Keji, Oduali Chineme, Williams Tunji, Agbogu George, Ogbunamiri Ken, Kalio Samuel, Gbaraneh Barry, Abiagom Victor, Salami Dele, Aiboni Elohor, Bisi Dere, Ndukwe Agwu, Ejiogu Charles, Akinwumi Femi, Ileagu Charles, Olayemi Sarah, Opusunju Augusta & Henri Jaspers.

The team thanks Vincent Nwabueze SPDC Principal Production Technologist and the Shell global waterflood team, Dave Chapelle & Niel O'Neill for their technical support in getting the water flood back on its feet again.

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- Field Water Injection Project Resuscitation Review- Nov 2007
- Reservoir surveillance mapping Process, Oct 2007

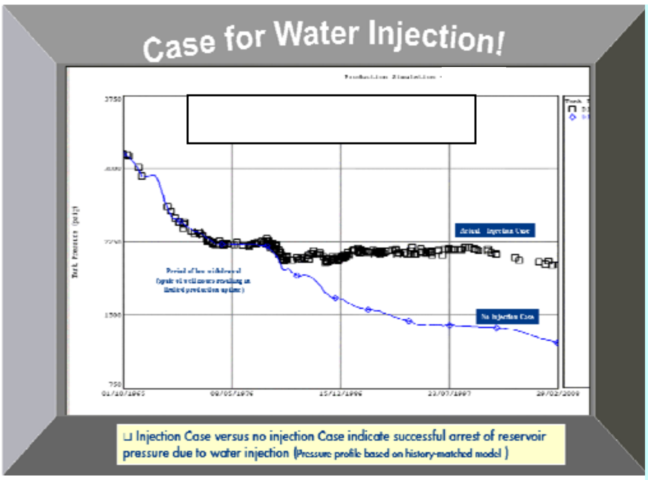

Figure 1: Reservoir Pressure Plot showing WI case (actual) versus "No WI" case (simulated)

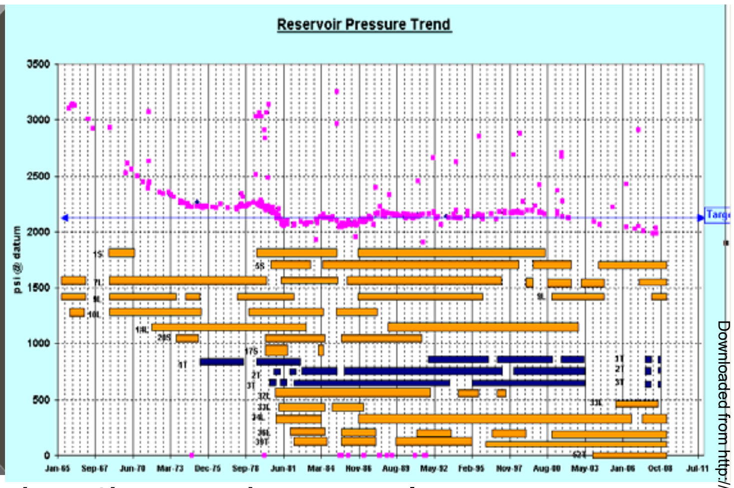

Figure 3b: Reservoir pressure plot + bars of production uptimes per conduit

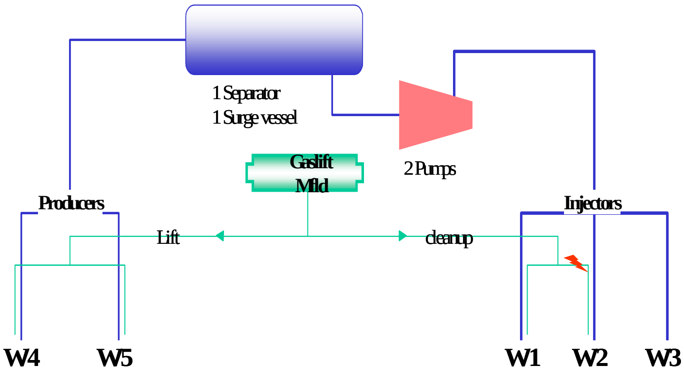

Figure 2: Water injection system Outlay

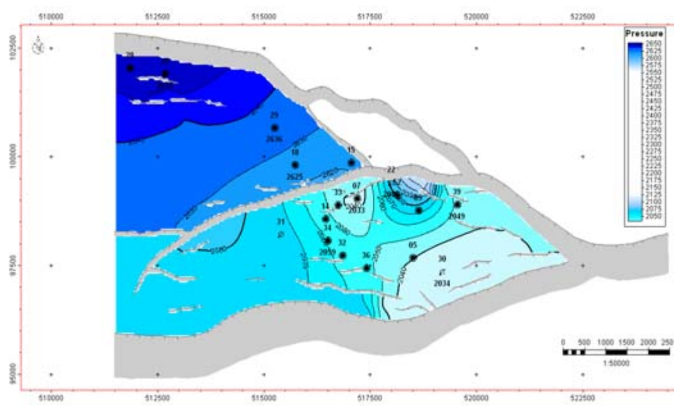

Figure 3c: Reservoir pressure map

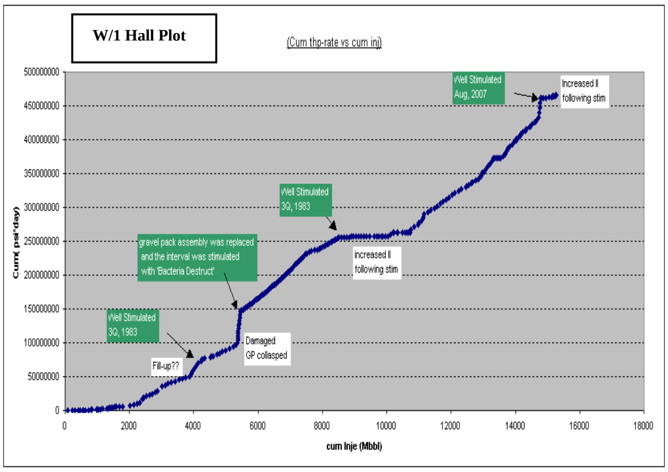

Figure 3a: Hall Plot –used to monitor injector performance

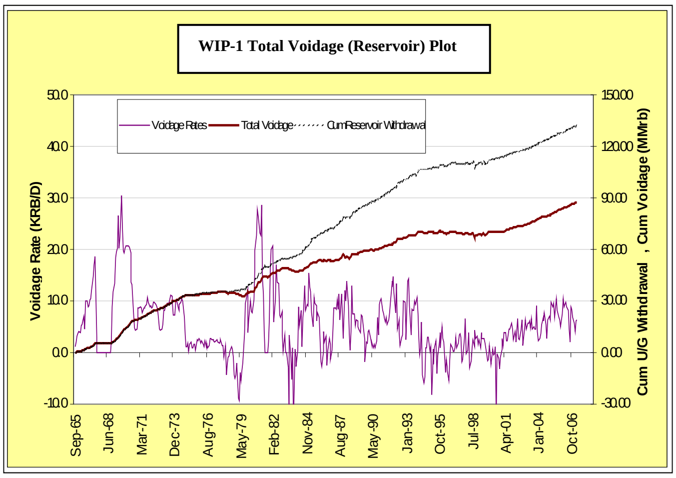

Figure 4: Reservoir Voidage Plot

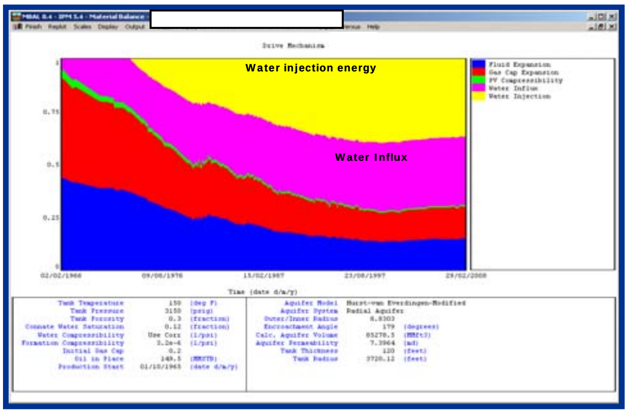

Figure 5: Reservoir Energy Plot

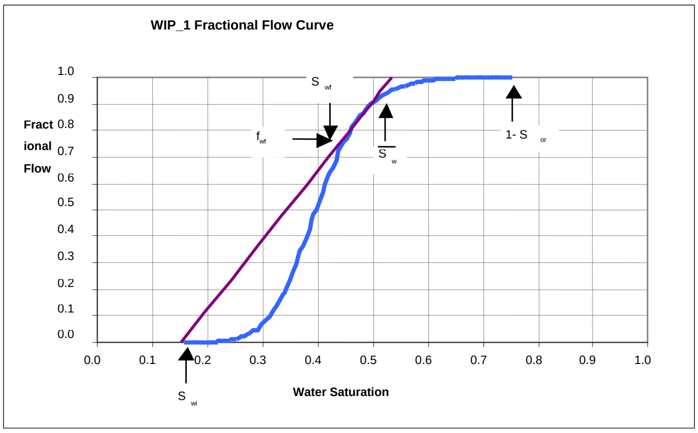

Figure 8a: Reservoir Fractional Flow Curve

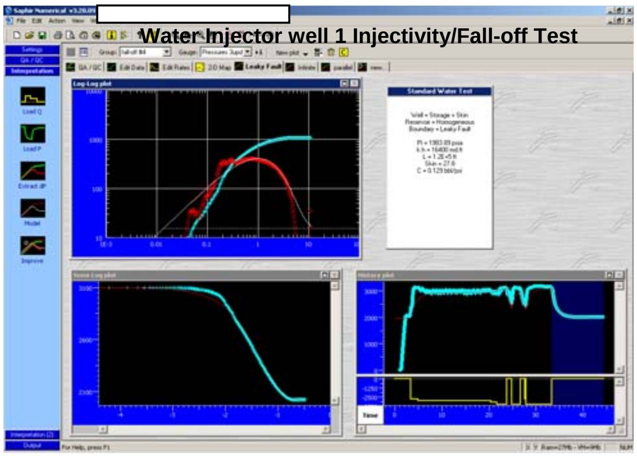

Figure 6: Well 1 Injectivity/Fall-up Test

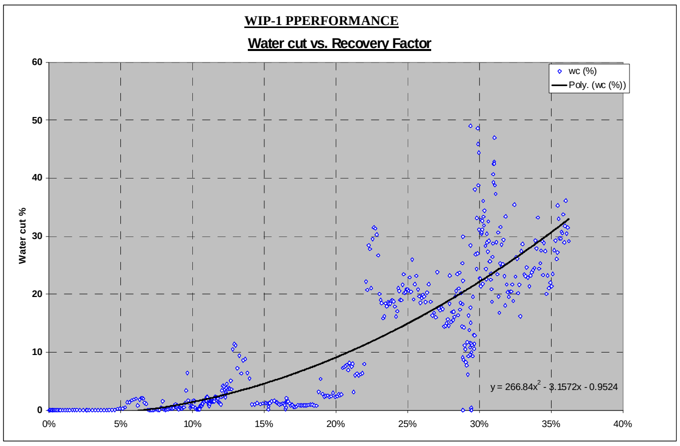

Figure 8b: Water cut vs. recovery trend

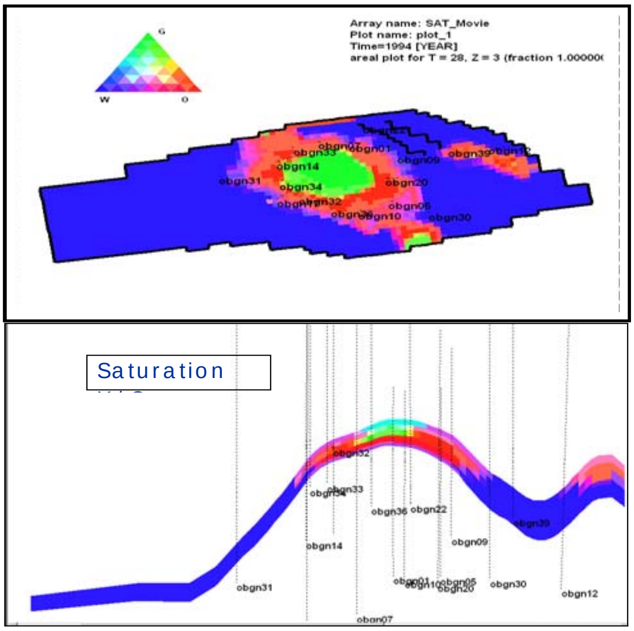

Figure 7: Reservoir Simulation Saturation Plots

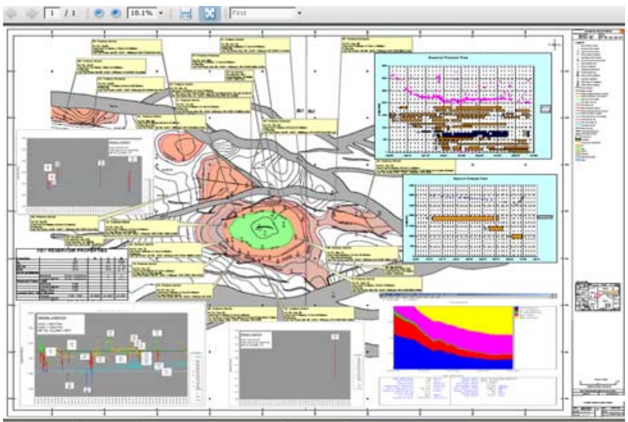

Figure 9: Reservoir Surveillance Map

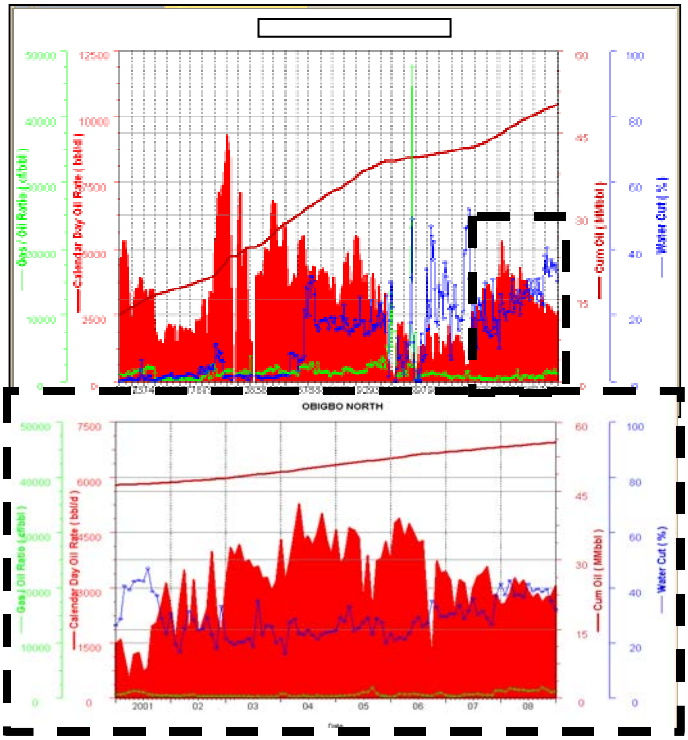

Figure 10: WIP_1 Production History
(a) Full history (b) Last 7 years vintage

Figure 11: Summary WIP_1 Water injection system SWOT analysis